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Environmental Conditions Responsible for Solar Activity

Final Technical Report

For the Period January 1, 1991 through June 30, 1998

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Summary

During the seven years that this program was active at Stanford University, the group working with Professor Sturrock investigated many aspects of the conditions responsible for solar activity. Their results are presented in detail in their publications. A list of publications, sorted by topic, is included in this report. The following is a very brief summary of the major advances.

Magnetic Field Structure and Analysis

One of the major problems concerning solar activity and its effect on Earth is that of coronal mass ejections (CMEs). These are believed arise from the sudden expansion of magnetic-field configurations. The final state appears to

be that of an open magnetic field. Sturrock proved analytically that the open state is in fact maximum-energy state of a semi-infinite magnetic field configuration. This result has the important consequence that it is not possible for magnetic field to be driven into a completely open state purely by magnetic stresses. This has proved to be an important guide in subsequent thinking about CMEs.

Glukhov, Klimchuk, Porter and Roumeliotis further developed the magneto-frictional method (created at Stanford in 1986) for calculating magnetic-field configurations. This technique was applied to study of the evolution of magnetic field configurations as they were progressively stressed. We examined a case related to CMEs, using a spherical geometry and an initially dipolar magnetic field, and then examined the development of the magnetic field when the northern and southern hemispheres are rotated in opposite directions, to simulate the foot-point shearing that is believed to be responsible for some CMEs. We obtained the surprising result that steady and slow motion of the footpoints could lead to a sudden eruption of the magnetic field. This may explain the origin of a certain class of CMEs.

Since our investigations led us to calculate the structure of highly stressed force-free field configurations, we decided to examine the asymptotic forms of force-free fields of translational and cylindrical symmetry. Sturrock derived formulas showing how the dimensions and energy of the field vary with continued surface displacements. Glukhov and Porter found that the analytical formulas obtained in this way are a good approximation to the results of our computer calculations.

Towards the end of this program, Roumeliotis developed what we consider to be an important new idea for reconstructing force-free magnetic fields from photospheric vector magnetograph data. This is called the "optimization function" approach. Subsequent study of this method has shown that it could lead to a practical procedure for calculating the coronal magnetic-field structure from photospheric vector magnetograph data. This could be very

helpful since many models of coronal magnetic fields have been investigated, to see if they lead to flares or CMEs. Hence one will be able to take advantage of those studies if one can calculate the actual structure of the coronal magnetic field, based on observational data.

Coronal Structure and Heating

There is an extensive literature concerning coronal heating, which nevertheless remains a major problem in solar physics. Since the corona is hotter and denser in active regions (which have strong magnetic fields) than in quiet regions (which have weak magnetic fields), there is a strong case that the corona is heated by MHD (magnetohydrodynamic) waves. However, there has been the difficulty that fast-mode MHD waves, which can carry sufficient energy to heat the corona, do not dissipate in the corona. Porter and Klimchuk were able to show that it is indeed possible for the corona to be heated by MHD waves, but they must be of much higher frequency than previously believed. This led us to look for processes which might excite high-frequency waves in the corona.

This led Sturrock to develop a new concept for coronal heating, that of "sudden magnetic relaxation." The basic idea is that, if two flux tubes reconnect at or near their foot-points, this will lead to the formation of a large flux tube that is far from equilibrium. The sudden relaxation of that flux tube towards its equilibrium state will then excite sound waves (and probably other types of waves also). These sound waves will then dissipate in the corona and lead to coronal heating.

We have carried out a number of calculations to evaluate this concept. We have developed the idea theoretically, and Parnell made a comparison of the coronal parameters and the relevant photospheric magnetic field strength. There appears to be good agreement between the theory and observational

data, and we find that this concept gives a good explanation both of the energy budget of the corona and of the mass flow into and out of the corona.

Flares, CMEs and Eruptions

Our study of the destabilization of force-free magnetic field configurations led to a promising interpretation of eruptive flares, in terms of the sudden expansion of a slowly stressed force-free field configuration. Sturrock further developed the idea that "tether-cutting" may play an important role in driving prominence eruptions and eruptive flares. The term refers to an analogy: if a hot-air balloon is held down by a number of weak ropes, and if one of the ropes snaps or is cut, the others may be too weak to hold the balloon in place so that they also snap and the balloon lifts off. A prominence may involve a cylindrical flux tube that is held in place by many magnetic connections to the photosphere. If some of these connections break, this may lead to a progressive breaking of the remaining connections so that the prominence lifts off, causing a CME.

Wheatland further developed the avalanche model of solar flares, originally developed by Russ Hamilton and Ed Lu at Stanford. The model involves a large array of cells, and rules according to which sudden energy release in one cell may trigger one or more energy-release events in neighboring cells. Earlier studies of this process implicitly considered only a single active region. Our development took into account the fact that flares occur in many different active regions of different sizes and energies. This led to a more realistic basis for the avalanche model, which should be helpful in future development of this theory.

Prominences

Antiochos and Klimchuk developed a theory for the condensation of coronal gas that can lead to the formation of solar prominences. Glukhov investigated the tearing instability of a neutral current sheet, such as exists

between the oppositely directed flux tubes in a helmet streamer, and developed a self-consistent model for the thermodynamic state of a helmet streamer.

Internal Dynamics

Solar activity is normally regarded as having its origin in events on the solar surface. However, the fact that sunspots develop as part of the overall solar cycle, and the fact that there are other cycles in solar activity, clearly indicates that there are major processes in the solar interior that determine the occurrence and properties of solar activity. We therefore attempted to better understand the nature of periodicity in solar activity, and to find other ways to probe the solar interior. This led Bai and Sturrock to study oscillations that occur with periods of 154 days (the Rieger oscillation), 77 days, and 51 days. We also undertook to search for such periodicities in solar neutrino data, since this is the only way of probing the internal magnetic field of the Sun.

Analysis by Sturrock, Walther and Wheatland led us to the conclusion that the solar neutrino flux does not vary with the solar cycle, contradicting a number of articles that had previously been published. We believe those articles were based on faulty statistics. However, we found evidence that the solar neutrino flux does vary with the rotational period of the Sun. This result, if it is confirmed by later studies, will provide strong evidence that neutrinos have non-zero magnetic moment and that they change their flavor in propagating through magnetized regions in the solar interior. This could potentially provide a method for probing the solar magnetic field deep in the convection zone. If this proves possible, it should lead to advance notice of the development of the solar cycle and it could possibly provide an early warning of the development of new active regions.

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